

New Stabilization Symmetries for Dark Matter

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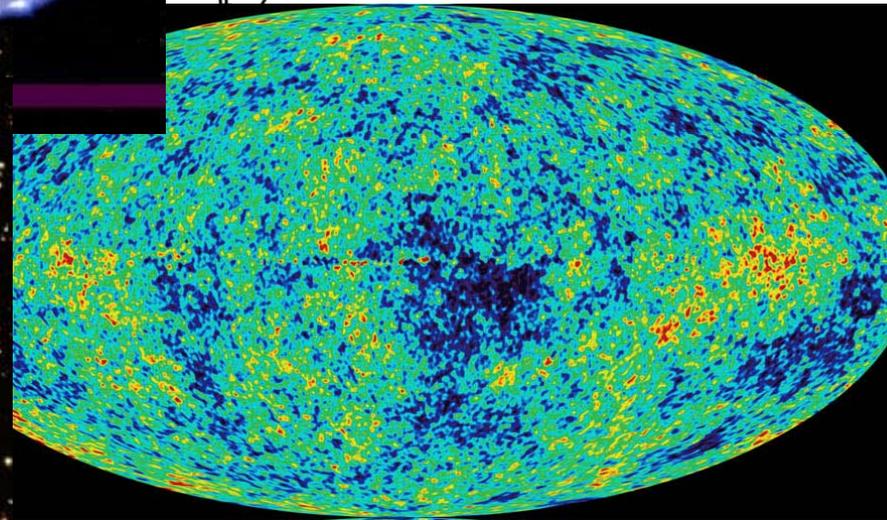
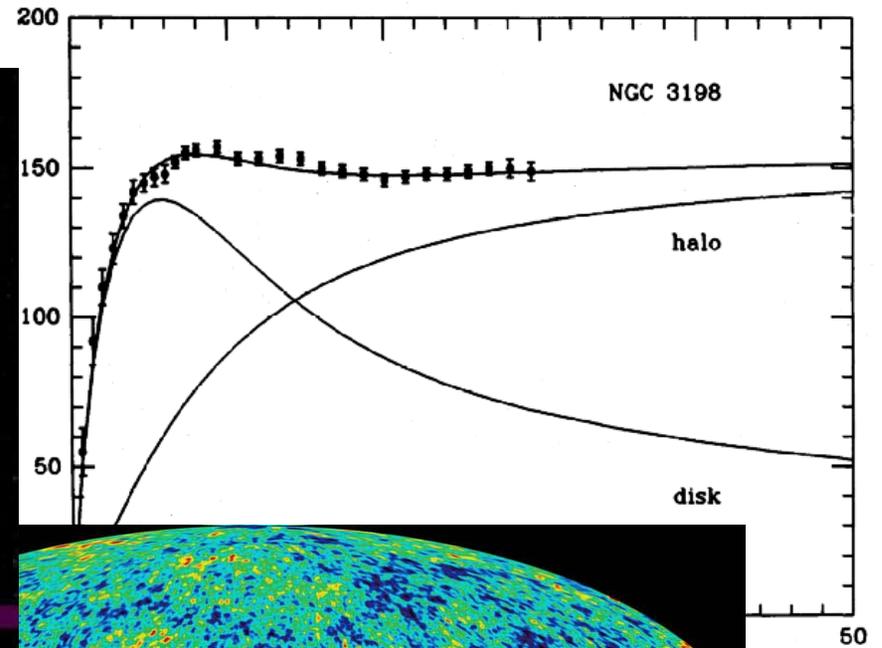
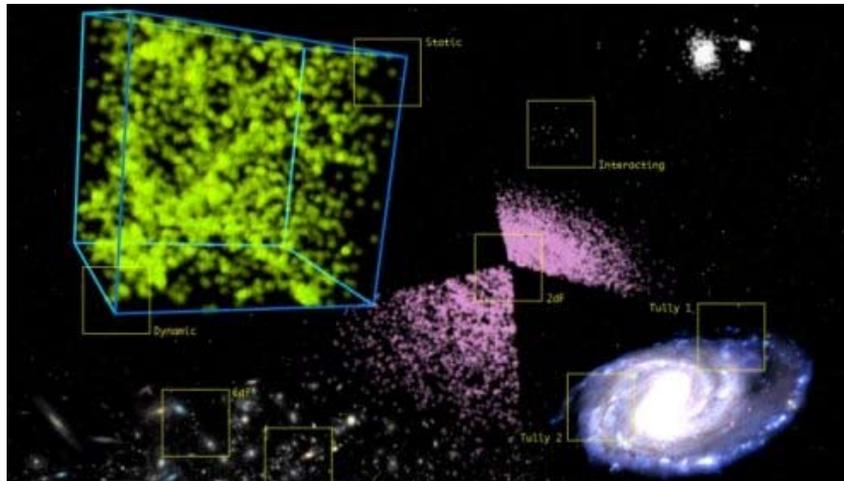
- arXiv:1007.0045

- to appear w. Adisorn Adulpravitchai

Summary

- Discrete symmetries can stabilize dark matter
 - Ad-hoc? More fundamental origin?
 - Abelian Z_2 common, other possibilities?
- Discrete gauge symmetry:
 - Discrete symmetry as a remnant of broken gauge symmetry
 - Survey models based on $U(1)$ broken to Z_N
- Nonabelian Discrete Symmetry:
 - Construct ‘minimal’ model based on group D_3
- New phenomena from new symmetries:
 - Cosmology, direct detection experiments, and colliders

Data inconsistent with the SM + GR



Canonical Dark Matter (WIMP) assumptions:

- Single new elementary particle
- Mass \sim weak scale
- Weakly interacting
- Thermal Relic
- Neutral under color, electromagnetism \implies either:
 - DM in $SU(2)_L \times U(1)_Y$ multiplet (such that $Q_{EM} = 0$)
 - DM in the hidden sector \implies I will focus on this possibility
- Stable \implies Dark symmetry
 - What is the symmetry?

Discrete Z_2 symmetry

- Most common example in literature.
 - R -parity, KK-parity, T -parity, ...

But...

- Ad-hoc
- What is the origin of Z_2 ?
- Why not other symmetries, e.g. Z_N , Nonabelian symmetries?

Bigger question:

What is the organizing principle for the dark sector?

Discrete Gauge Symmetries

BB, [arXiv:1007.0045](#)

Prior work relevant for Dark Matter

- SUSY, R-parity, and alternatives

Ibanez, Ross '91, '92

Martin '92, '96

Dreiner, Luhn, Thormeier '05

and many others

- Z_2 from $SU(2)$ gauge symmetry and collider signals

Walker '09

Agashe, Kim, Toharia, Walker '10

Discrete gauge symmetries

Krauss, Wilczek '90

Prototype model:

- $U(1)_D$ gauge symmetry
- Matter fields χ , with $U(1)_D$ charge $Q_\chi = 1$
- Higgs field ϕ , with charge $Q_\phi = N$
- $U(1)_D$ symmetry breaking: $\langle \phi \rangle = v'/2$

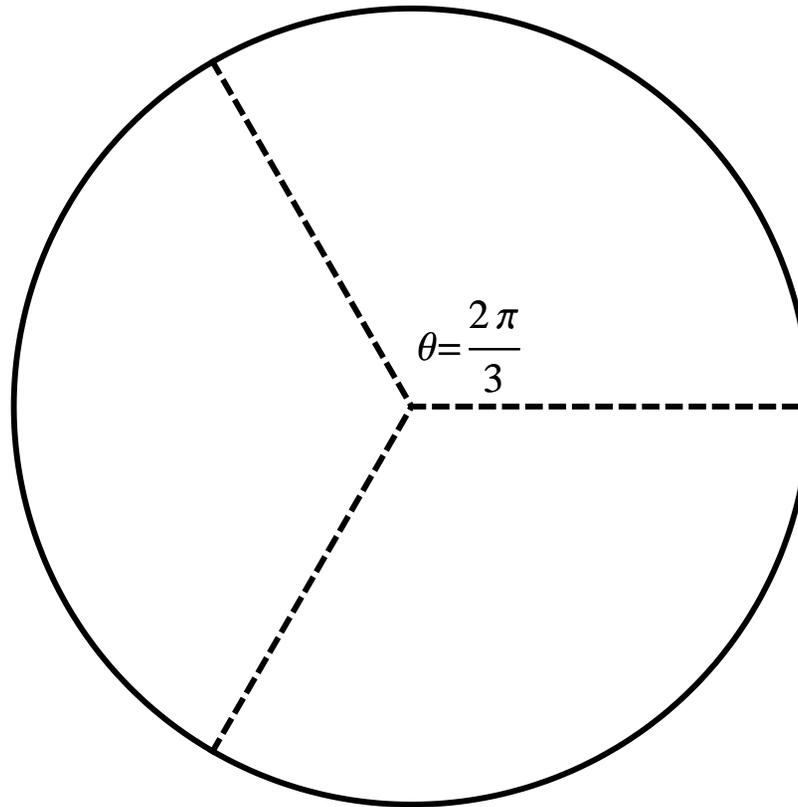
$$\mathcal{L} \supset \phi^\dagger \chi^N + \text{h.c.} \rightarrow v' \chi^N + \text{h.c.}$$

- Remnant Z_N symmetry:

$$\chi \rightarrow e^{2\pi i/N} \chi$$

e.g. Z_3

Rotation by phase $2\pi/3$:



How to talk to the dark sector:

- “Connector” particle - charged under both sectors
- Higher dimensional operators
- Portals

$$\begin{array}{ll} B_{\mu\nu} V^{\mu\nu} & \text{U(1) portal Holdom '86 ,} \\ H^\dagger H (A S + B S^2) & \text{Higgs portal ,} \\ L H N & \text{Neutrino portal ,} \end{array}$$

- $U(1)_D$ symmetry \implies vector and Higgs portals available!

General $U(1)_D$ Lagrangian

$$\mathcal{L} = \mathcal{L}_D + \mathcal{L}_\chi + \mathcal{L}_{portal} + \Delta\mathcal{L}$$

$$\mathcal{L}_D = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + (D_\mu\phi)^\dagger(D^\mu\phi) + \mu_\phi^2\phi^\dagger\phi - \lambda_\phi(\phi^\dagger\phi)^2$$

$$\mathcal{L}_\chi = \begin{cases} (D_\mu\chi_i)^\dagger(D^\mu\chi_i) - m_i^2\chi_i^\dagger\chi_i - \lambda_i(\chi_i^\dagger\chi_i)^2 \\ i\bar{\chi}_i\bar{\sigma}^\mu D_\mu\chi_i \end{cases}$$

$$\begin{aligned} \mathcal{L}_{portal} = & -\frac{\kappa}{2}V_{\mu\nu}B^{\mu\nu} - 2\lambda_1(H^\dagger H)(\phi^\dagger\phi) \\ & -2\lambda_{2(i)}(H^\dagger H)(\chi_i^\dagger\chi_i) - 2\lambda_{3(i)}(\chi_i^\dagger\chi_i)(\phi^\dagger\phi) \end{aligned}$$

$\Delta\mathcal{L}$ contains nontrivial Z_N terms

Single field models

- Only 3 possibilities at the renormalizable level

– Scalar

$$Z_2 : \Delta\mathcal{L} = \lambda\phi_2^\dagger\chi_1\chi_1 + \text{h.c.}$$

$$Z_3 : \Delta\mathcal{L} = \lambda\phi_3^\dagger\chi_1\chi_1\chi_1 + \text{h.c.}$$

– Fermion

$$Z_2 : \Delta\mathcal{L} = -m_D\psi_1\xi_{-1} \\ -\lambda_L\phi_2^\dagger\psi_1\psi_1 - \lambda_R\phi_2\xi_{-1}\xi_{-1} + \text{h.c.}$$

Multi-field models

- Renormalizable Z_N models possible
- Multiple discrete symmetries \implies **Multi-component DM**
 - Example: Z_4 - Higgs ϕ_4 ; Dark matter χ_1, χ_2

$$\Delta\mathcal{L} \sim \phi_4^\dagger \chi_2 \chi_2 + \phi_4^\dagger \chi_2 \chi_1 \chi_1 + \chi_2^\dagger \chi_1 \chi_1 + \text{h.c.}$$

- Both Z_4 and Z_2 symmetry ($\chi_1 \rightarrow -\chi_1$)
- Lightest Z_4 and Z_2 particles stable and DM candidates

Chiral models

- Chiral set: Fermion content chosen so that anomalies cancel and vectorlike mass terms forbidden

Batra, Dobrescu, Spivak '05

$$\sum_i Q_i^3 = 0,$$

$$\sum_i Q_i = 0,$$

$$Q_i + Q_j \neq 0, \quad \text{for all } i, j .$$

- Need dark Higgs sector to break $U(1)_D$ and generate masses

Chiral models - Example

- Dark matter: $\psi_{-1}^i, \psi_3, \psi_4, \psi_{-6}^i, \psi_7$ where $i = 1, 2$
- Dark Higgs: ϕ_7

$$\Delta\mathcal{L} = -\lambda_a^{ij} \phi_7 \psi_{-1}^i \psi_{-6}^j - \lambda_b \phi_7^\dagger \psi_3 \psi_4 + \text{h.c.}$$

- ψ_7 ? like neutrino: form gauge invariant operator $\phi_7^\dagger \psi_7$ and generate majorana mass (higher dimension operator) or Dirac mass (introduce singlet ξ_0)
- Both Z_7 and accidental global 'flavor' symmetries stabilize DM (multi-component)

Mass splitting

- e.g. Z_2 scalar:

$$\chi_1 = \frac{1}{\sqrt{2}}(S + iP)$$

$$-\lambda(\phi_2^\dagger \chi_1 \chi_1 + \text{h.c.}) \rightarrow -\Delta m^2(S^2 - P^2),$$

- Both S, P odd under $Z_2 \rightarrow$ lightest is the DM candidate
- Off diagonal gauge interaction:

$$(D_\mu \chi)^\dagger (D^\mu \chi) \supset g_D V_\mu (P \partial^\mu S - S \partial^\mu P)$$

- Inelastic scattering
- Allows decay of Z_N partner: $P \rightarrow V_\mu^* S$

Smith, Weiner '01

Mass mixing

- e.g. Z_N multi-field:

$$-\lambda(\phi_N^\dagger \chi_Q^\dagger \chi_{N+Q} + \text{h.c.}) \rightarrow -\Delta m^2 \chi_Q^\dagger \chi_{N+Q} + \text{h.c.},$$

- Diagonalize by orthogonal transformation, with angle θ_χ
- Off-diagonal gauge and Higgs interactions, e.g.

$$\begin{aligned}
 & ig_D V_\mu(\chi_Q^\dagger, \chi_{N+Q}^\dagger) \leftrightarrow \partial_\mu \begin{pmatrix} Q & 0 \\ 0 & Q+N \end{pmatrix} \begin{pmatrix} \chi_Q \\ \chi_{N+Q} \end{pmatrix} \\
 \rightarrow & ig_D V_\mu(\chi_1^\dagger, \chi_2^\dagger) \leftrightarrow \partial_\mu \begin{pmatrix} Q + s_\chi^2 N & N s_\chi c_\chi \\ N s_\chi c_\chi & N + Q - s_\chi^2 N \end{pmatrix} \begin{pmatrix} \chi_1 \\ \chi_2 \end{pmatrix}
 \end{aligned}$$

Dark Matter phenomenology

- Relic Abundance:
 - 1) Annihilation into hidden sector: $\chi_j\chi_j \rightarrow VV, Vh', hh, \dots$
 - 2) Annihilation into SM via portals: $\chi\chi \rightarrow V^*, h^* \rightarrow \bar{\psi}_{SM}\psi_{SM}$
- Direct Detection via portals:
 - Nuclear scattering mediated via kinetic mixing, Higgs portal
 - ‘Vanilla’ Elastic, Inelastic, Form-factor, Momentum Dependent, light GeV DM, ...
- Indirect detection:
 - Dark Forces, Solar electronic signatures

Direct detection of multi-component DM

Naively, dominant cosmic component favored, but...

- Rate depends on relic abundance, DM mass, and scattering cross section

$$R_i \sim \frac{\rho_i \sigma_{N(i)}}{m_i}$$

- Big $\langle \sigma v \rangle_{ann}$ may suggest big σ_N
- Dominant component may be heavy \longrightarrow smaller number density
- Dominant component may scatter inelastically \implies smaller σ_N , different shape of recoil spectrum

e.g. $Z_6 \cong Z_3 \times Z_2$ model

- Dark Matter: $\chi_2, \chi_3 = \frac{1}{\sqrt{2}}(S + iP)$
Dark Higgs: ϕ_6

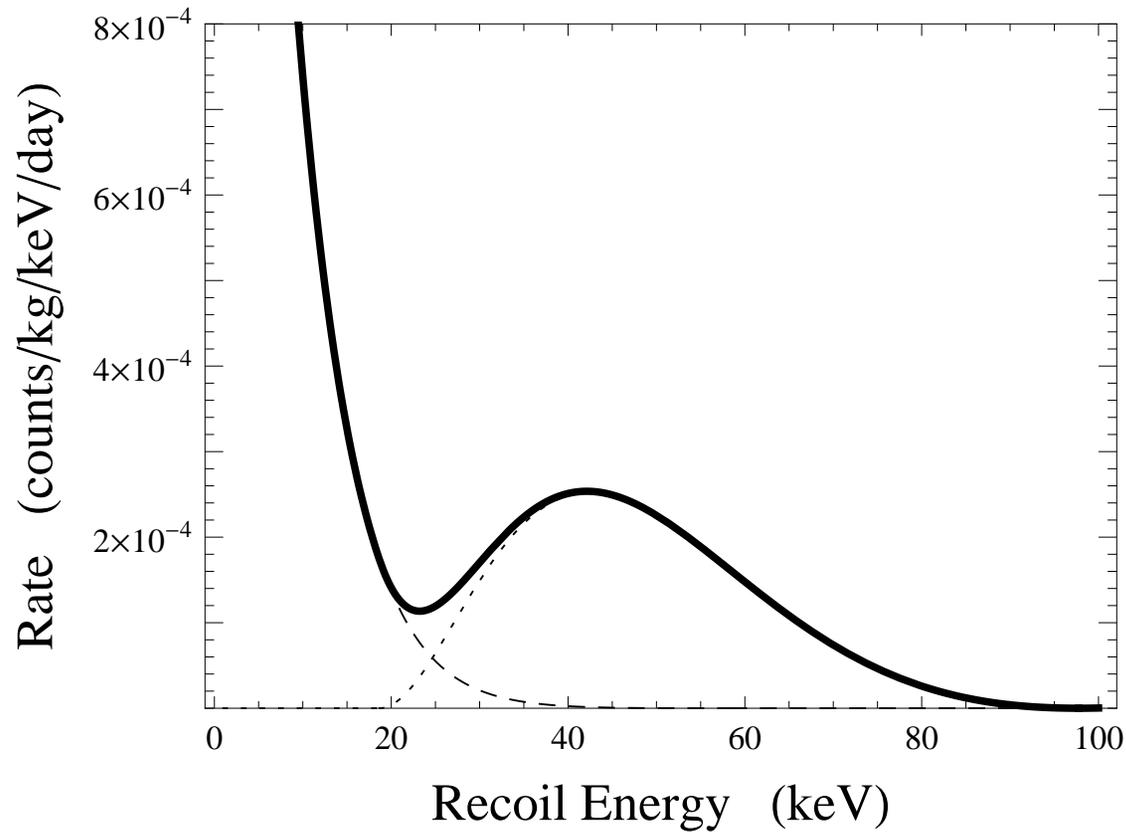
- Nuclear scattering through kinetic mixing portal
 - Small mass splitting $\implies S$ scatters inelastically
 - χ_2 scatters elastically

$$\sigma_N \simeq \frac{16\pi Z^2 \alpha \alpha' \kappa^2 \mu_N^2}{m_V^4} \sqrt{1 - \frac{\delta}{\mu_N v^2/2}}$$

- Relic abundance: annihilation into dark vectors $\chi\bar{\chi} \rightarrow VV$

$$\Omega h^2 \sim \frac{1}{\langle \sigma v \rangle_{ann}} \sim \frac{m_\chi^2}{\pi \alpha_D^2}$$

$$m_S = 3 \text{ TeV}, m_{\chi_3} = 30 \text{ GeV}, \delta = 150 \text{ keV}$$

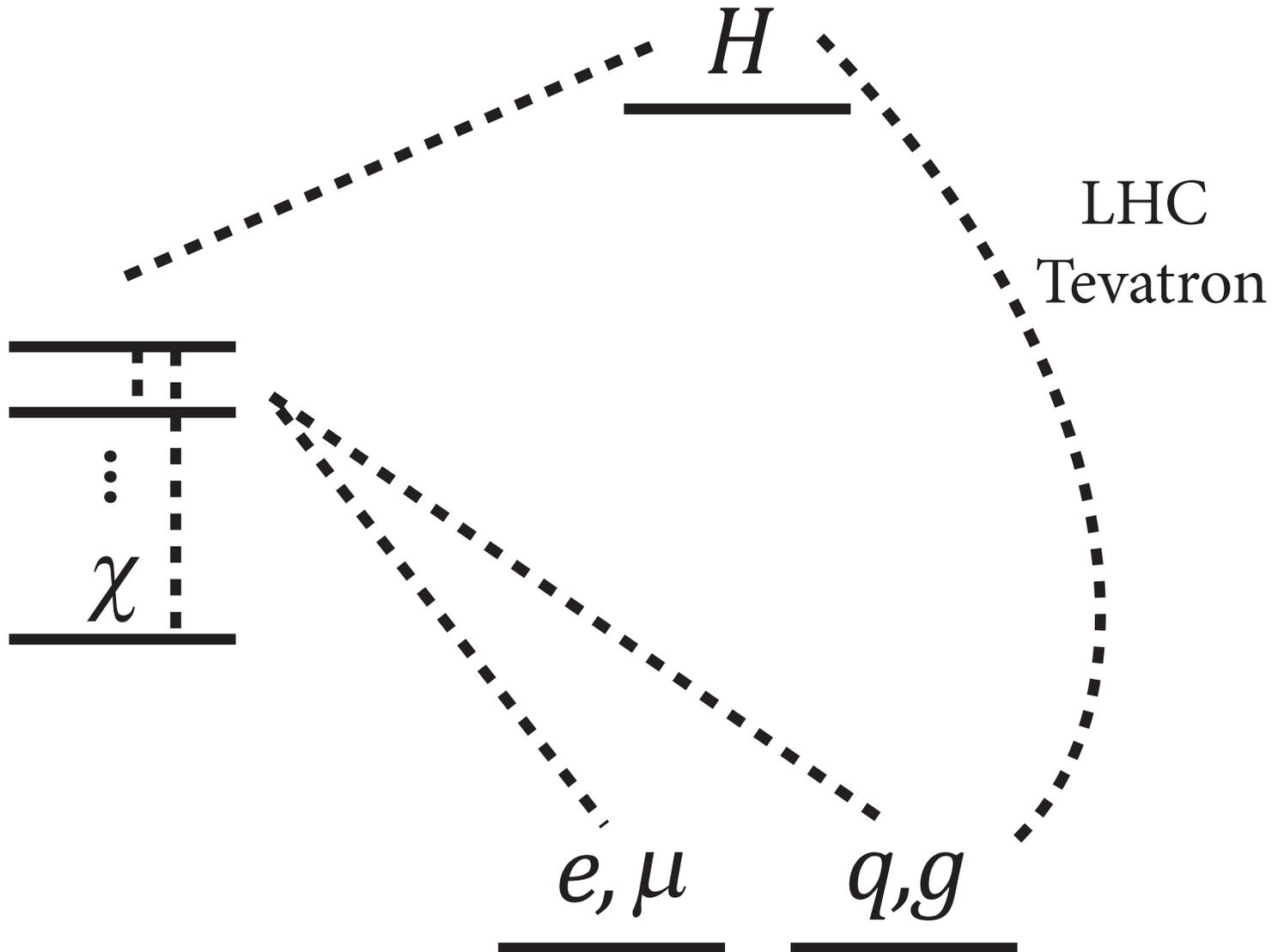


- Recoil spectrum similar to 'semi-elastic' scattering

Krohn, Ruderman, Wang '10

Hidden valley via Higgs

Strassler, Zurek '06



Higgs decays and new physics

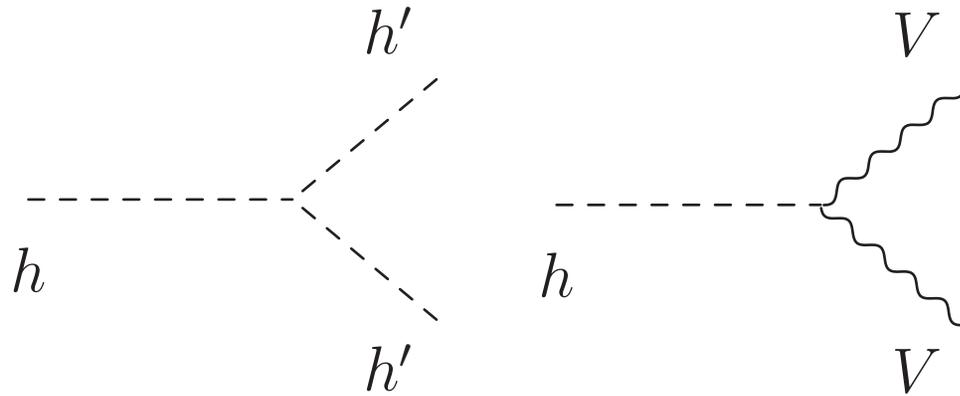
- Dominant mode for a light h in SM: $h \rightarrow b\bar{b}$,

$$\Gamma_{b\bar{b}} \simeq \frac{3}{16\pi} y_b^2 m_h$$

General Observation: It is easy for the Higgs to decay to new light states - we are competing with bottom Yukawa, $y_b \sim 1/40$.

Direct decays to h' , V_μ

$$\Delta\mathcal{L} \supset \lambda_1(H^\dagger H)(\phi^\dagger\phi)$$

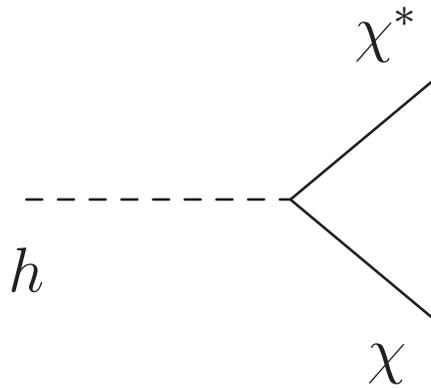


- Compare with $h \rightarrow b\bar{b}$:

$$\frac{\Gamma_{(h'h',VV)}}{\Gamma_{b\bar{b}}} \sim \frac{v^2}{m_h^2} \left(\frac{\lambda_1^2}{y_b^2} \right)$$

Direct decays to χ

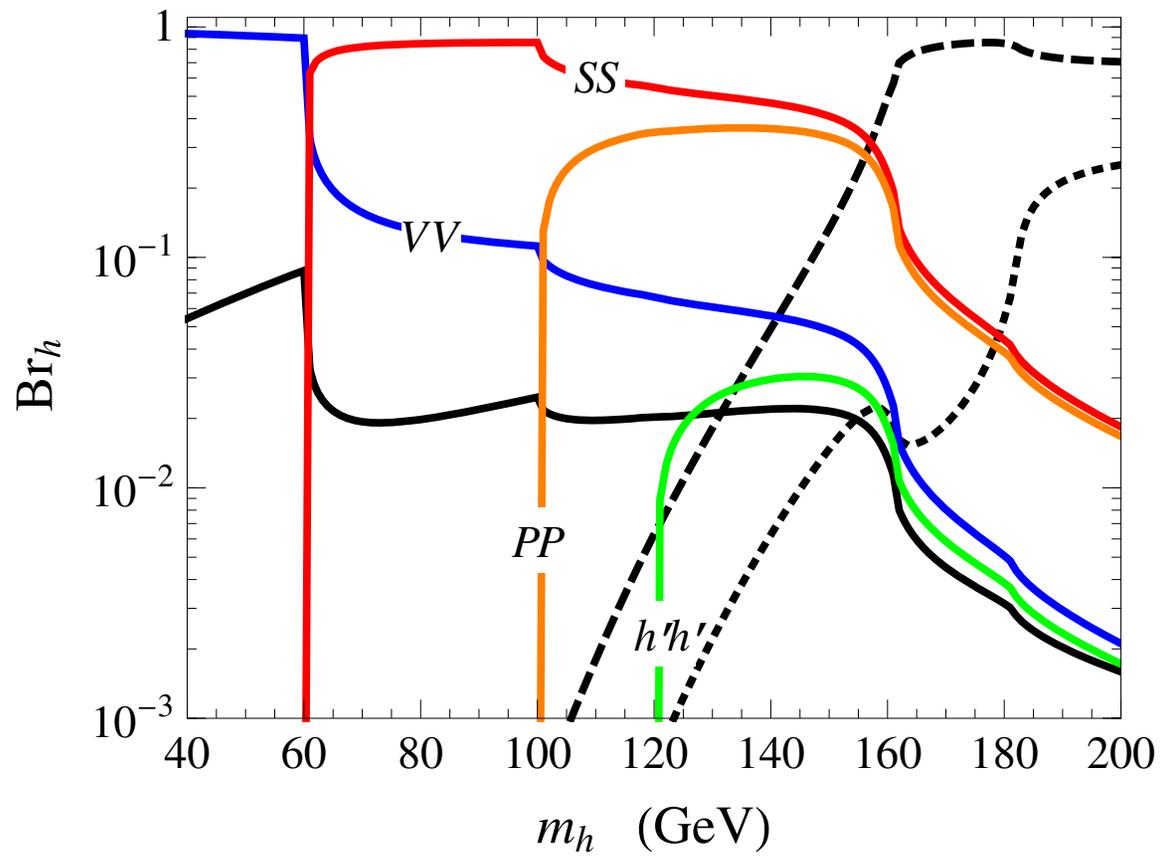
$$\Delta\mathcal{L} \supset \lambda_2(H^\dagger H)(\chi^\dagger\chi)$$



- Compare with $h \rightarrow b\bar{b}$:

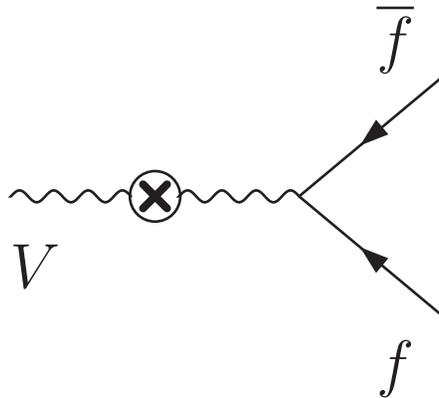
$$\frac{\Gamma_{\chi^*\chi}}{\Gamma_{b\bar{b}}} \sim \frac{v^2}{m_h^2} \left(\frac{\lambda_2^2}{y_b^2} \right)$$

Example Z_2 scalar DM



Cascades: Gauge boson V_μ

- If $m_V < 2m_{\chi_i}$, then $V_\mu \rightarrow \bar{\psi}_{SM}\psi_{SM}$ via kinetic mixing. This is prompt for $\kappa > 10^{-5}$. The branching to leptons is $O(1)$ fraction.



- If $m_V > 2m_{\chi_i}$, then V_μ decays to DM and Z_N partners

Cascades: Dark Higgs h'

- If h' is the lightest state in dark sector, then $h' \rightarrow \bar{\psi}_{SM}\psi_{SM}$ via:
 - Loop of V ; h' is collider stable,
 - Higgs portal; decay is prompt if $\theta > 10^{-3}$.
- If $m_{h'} > m_V$, then $h' \rightarrow VV^* \rightarrow 4\psi_{SM}$; may be displaced for three body decay.
- If $m_{h'} > 2m_{\chi_i}$, then decays to DM and Z_N partners compete with VV mode; prompt decay

Cascades: Z_N partners χ_i

- If additional symmetries present, e.g. accidental or subgroup of Z_N , additional partners χ_i maybe stable.
- If mass mixing/splitting between matter, vertex $V\chi_i\chi_j$ or $h'\chi_i\chi_j$ exists and allows decay $\chi_j \rightarrow \chi_i V^* \rightarrow \chi_i \bar{\psi}_{SM} \psi_{SM}$, etc. Vector may be offshell and lead to displaced vertices even for large mixings.
- May have vertices $\chi_i\chi_j\chi_k$, etc, which allow cascades into lighter DM, Z_N partners.

Many possible signatures of the Higgs ...

- $h \rightarrow \chi\chi$

Eboli, Zeppenfeld '00

- $h \rightarrow VV \rightarrow 4l$

Gopalakrishna, Jung, Wells '08

- $h \rightarrow h'h' \rightarrow 4\chi' \rightarrow 8l + 4\chi$

- $h \rightarrow$ lepton jets

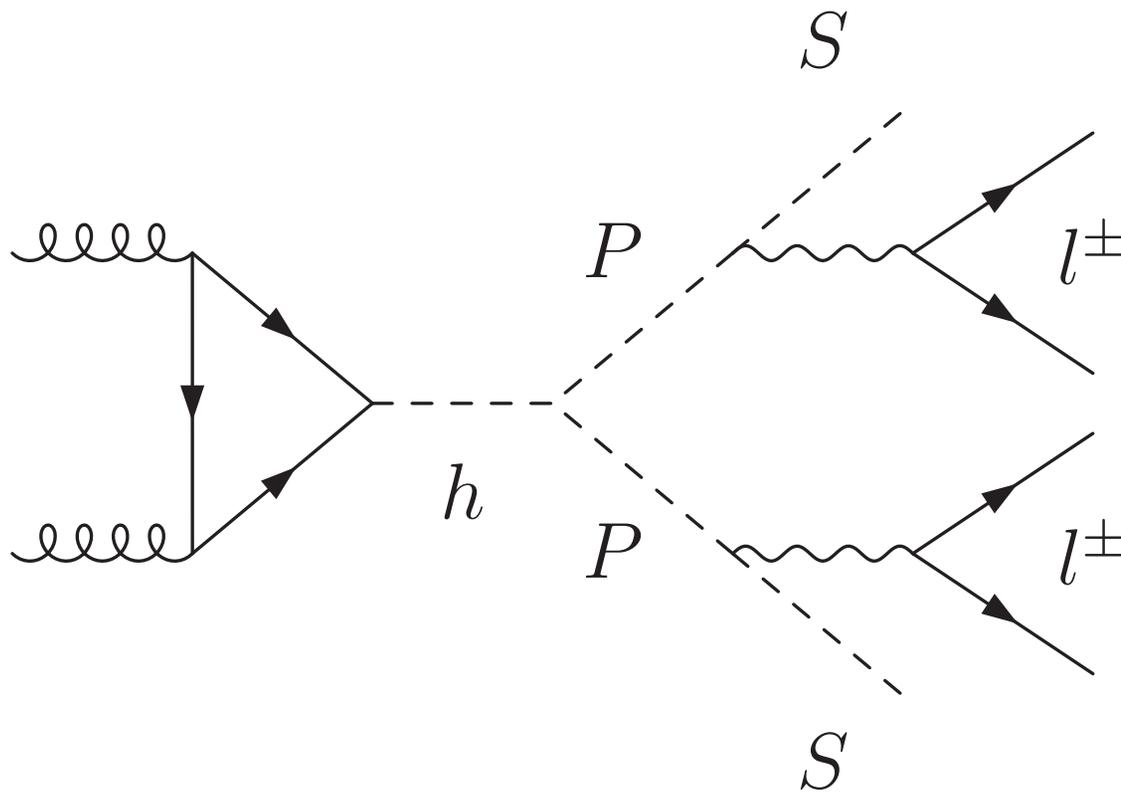
Falkowski, Ruderman, Volansky, Zupan '10

- $h \rightarrow \dots \rightarrow \chi_1\chi_2 + nl$

Konar, Kong, Matchev, Park '09

and so on...

e.g. Z_2 scalar: $pp \rightarrow h \rightarrow PP \rightarrow 4l^\pm + \cancel{E}_T$



Nonabelian Discrete Symmetries

Work in Progress

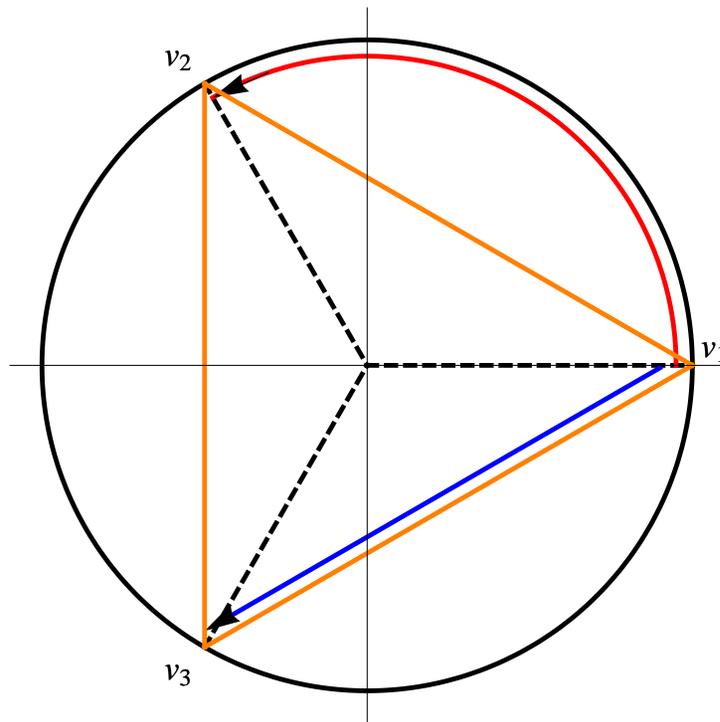
Finite Groups

Order	Abelian	Nonabelian
2	Z_2	-
3	Z_3	-
4	$Z_4, Z_2 \times Z_2$	-
5	Z_5	-
6	Z_6	D_3
7	Z_7	-
8	$Z_8, Z_2 \times Z_4, Z_2 \times Z_2 \times Z_2$	D_4, Q_8
9	$Z_9, Z_3 \times Z_3,$	-
10	Z_{10}	D_5
11	Z_{11}	-
12	$Z_{12}, Z_2 \times Z_6$	A_4, D_6, T
\vdots	\vdots	\vdots

D_3 : Dihedral group of order 6

Symmetries of the equilateral triangle:

- Rotations in the plane by $\theta = 2\pi/3$
- Rotations about symmetry axes by $\theta = \pi$



Two Generators of D_3 , A , B

$$A^3 = 1, \quad B^2 = 1, \quad ABA = B$$

Representations of D_3 :

- Singlet $\underline{1}_1$: $A = B = 1$ (trivial)
- Singlet $\underline{1}_2$, $A = 1$, $B = -1$
- Doublet $\underline{2}$

$$A = \begin{pmatrix} e^{2\pi i/3} & 0 \\ 0 & e^{-2\pi i/3} \end{pmatrix}, \quad B = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

Minimal D_3 model of dark matter

Fields:

$$\underline{\mathbf{1}}_2 : \quad \eta$$

$$\underline{\mathbf{2}} : \quad X \equiv \begin{pmatrix} \chi \\ \chi^* \end{pmatrix}$$

Lagrangian:

$$\mathcal{L}_{kin} = (D_\mu H)^\dagger (D^\mu H) + \frac{1}{2}(\partial_\mu \eta)^2 + (\partial_\mu \chi)^* (\partial^\mu \chi)$$

$$\begin{aligned} V(H, \eta, \chi) = & m_1^2 H^\dagger H + \frac{1}{2} m_2^2 \eta^2 + m_3^2 \chi^* \chi + \frac{\mu_1}{3!} (\chi^3 + \chi^{*3}) \\ & + \lambda_1 (H^\dagger H)^2 + \frac{\lambda_2}{4} \eta^4 + \lambda_3 (\chi^* \chi)^2 \\ & + \alpha_1 (H^\dagger H) \eta^2 + 2\alpha_2 (H^\dagger H) (\chi^* \chi) + \alpha_3 \eta^2 (\chi^* \chi) + \frac{i\alpha_4}{3!} \eta (\chi^3 - \chi^{*3}) \end{aligned}$$

Note:

- Theory with only η or $\chi \implies$ still viable DM, but ‘trivial’ under D_3
- $D_3 \subset SO(3)$, and $\mathbf{3} = \underline{\mathbf{1}}_2 \oplus \underline{\mathbf{2}}$, so if D_3 is a discrete gauge symmetry, one might expect both η and χ
- Nontrivial under D_3 :

$$\frac{i\alpha_4}{3!}\eta(\chi^3 - \chi^{*3})$$

- $m_\eta > 3m_\chi$:
 - $\eta \rightarrow 3\chi, 3\chi^*$ decays and χ is the only DM candidate
- $m_\eta < 3m_\chi$:
 - η is stable and there are two DM candidates

Relic Abundance

- η :

$$\eta\eta \rightarrow X_{SM}, \quad \eta\eta \rightarrow \chi\chi^*, \quad \eta\chi \rightarrow \chi^*\chi^*, \quad \eta\chi^* \rightarrow \chi\chi$$

- χ :

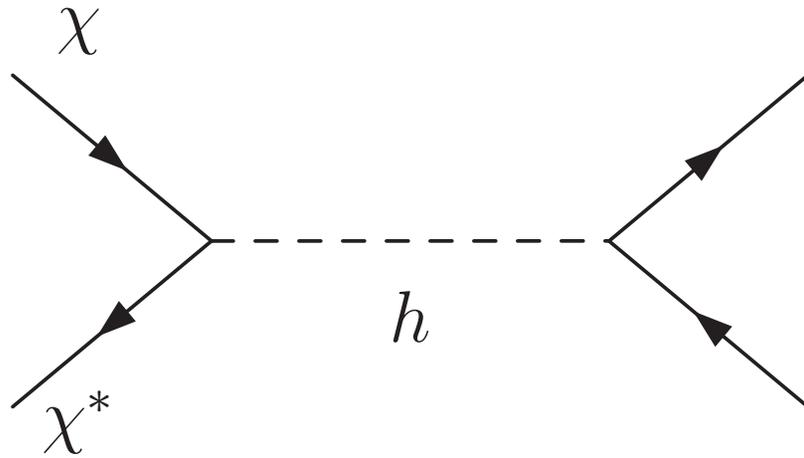
$$\begin{aligned} \chi\chi^* &\rightarrow X_{SM}, & \chi\chi &\rightarrow h\chi^*, & \chi h &\rightarrow \chi^*\chi^*, \\ \chi\chi^* &\rightarrow \eta\eta, & \chi\chi &\rightarrow \eta\chi^*, & \chi\eta &\rightarrow \chi^*\chi^* \end{aligned}$$

where $X_{SM} = t\bar{t}, hh, ZZ, WW, b\bar{b} \dots$

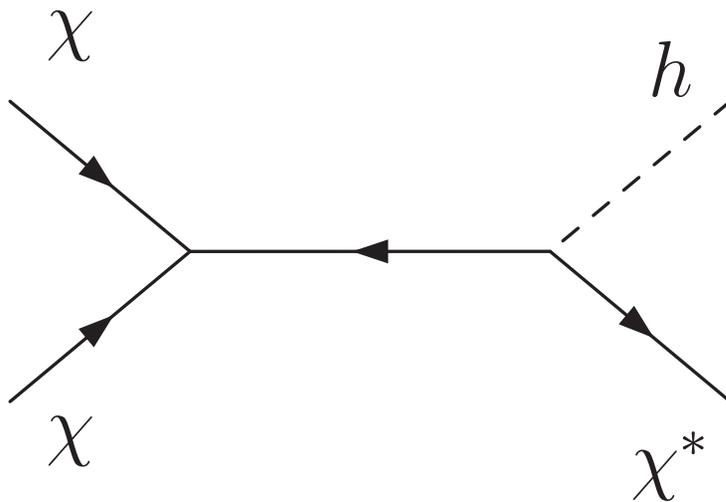
- Dark matter conversion and 'semi-annihilation'

D'Eramo, Thaler '10

Case 1: η heavy, $\mu_1 \neq 0$: Semi-annihilation



$$X_{SM} = t\bar{t}, hh, ZZ, WW, b\bar{b} \dots$$



$$+ t + u$$

Case 1: η heavy, $\mu_1 \neq 0$: Semi-annihilation

- Boltzmann Equations:

$$\frac{dn_\chi}{dt} + 3Hn_\chi = C_{\chi\chi^* \rightarrow X_{SM}} + C_{\chi\chi \rightarrow h\chi^*} + C_{\chi h \rightarrow \chi^*\chi^*}$$

- Collision terms:

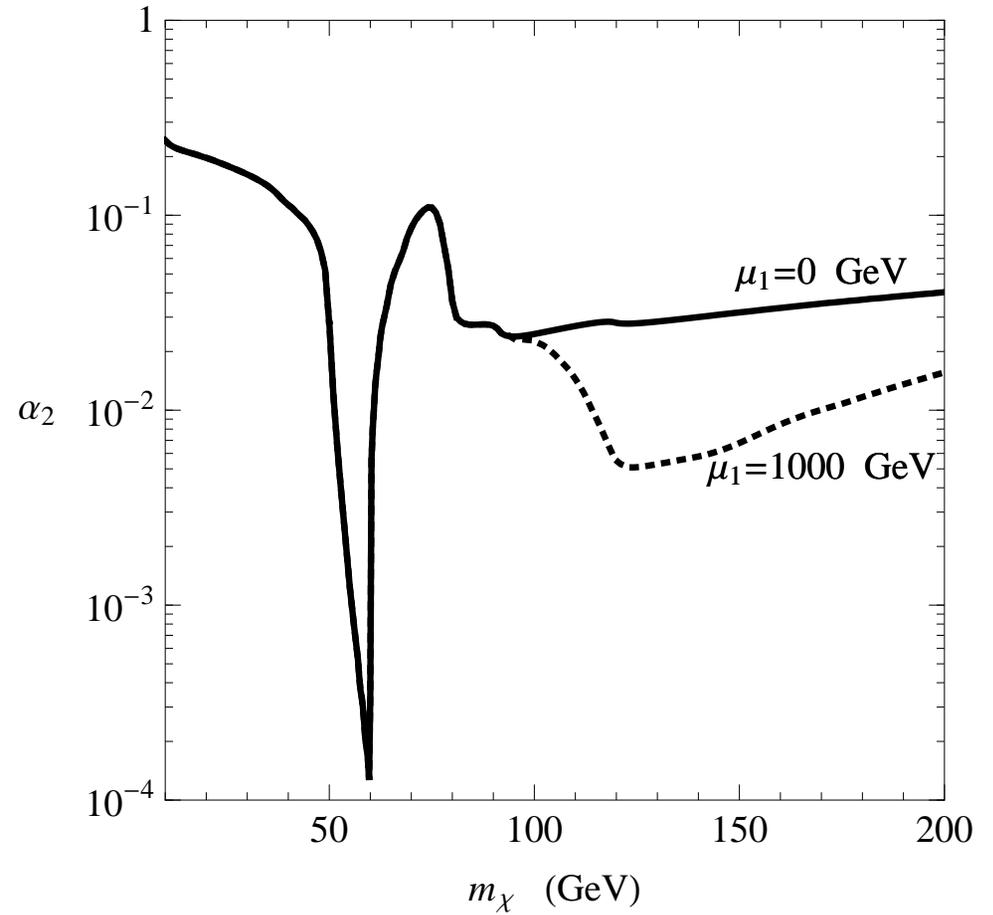
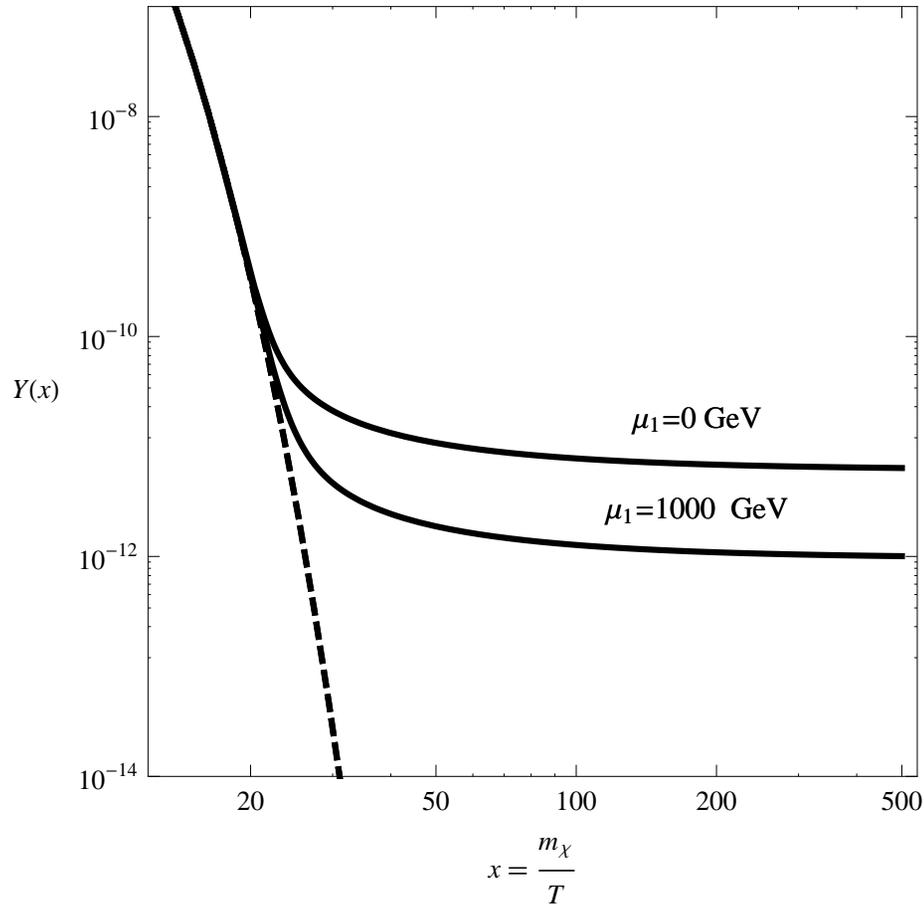
$$C_{\chi\chi^* \rightarrow X_{SM}} = -\langle\sigma v\rangle_{\chi\chi^* \rightarrow X_{SM}} \left[n_\chi^2 - n_\chi^{\text{eq}2} \right],$$

$$C_{\chi\chi \rightarrow h\chi^*} = -\langle\sigma v\rangle_{\chi\chi \rightarrow h\chi^*} \left[n_\chi^2 - n_\chi n_\chi^{\text{eq}} \right],$$

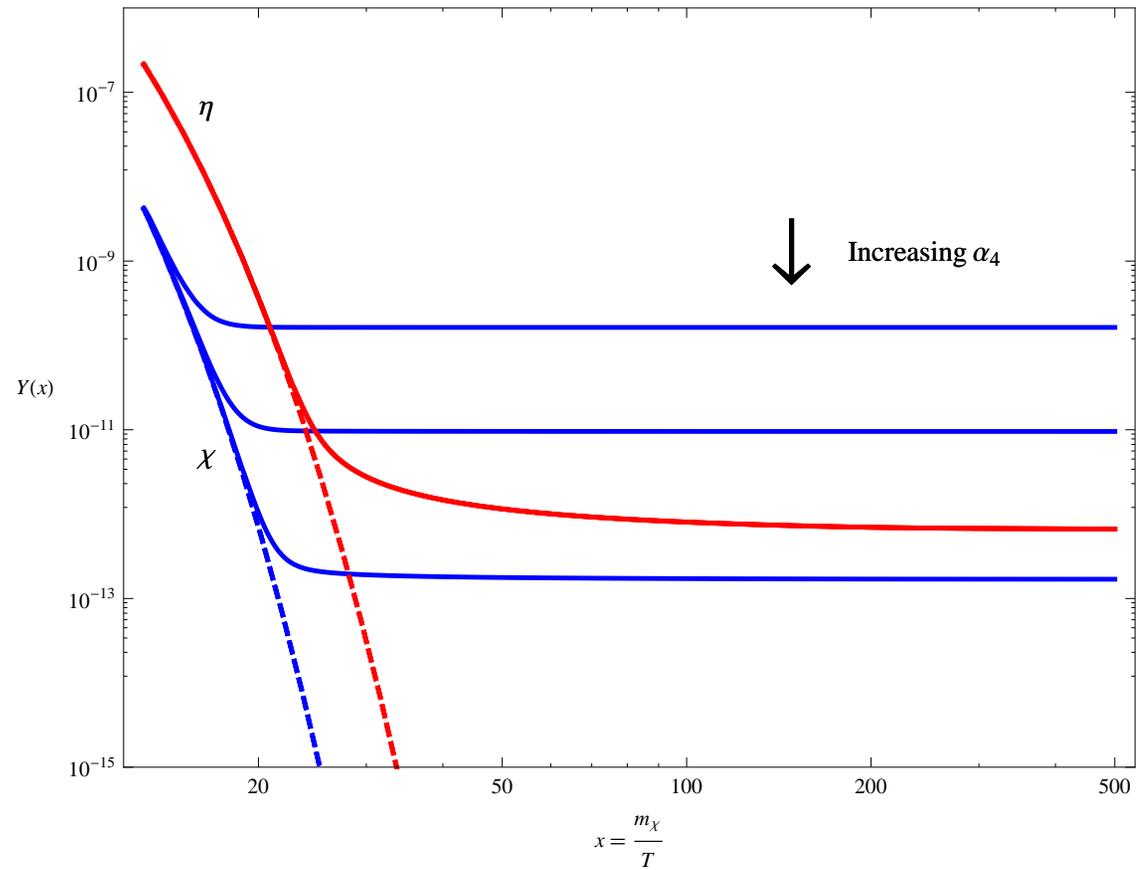
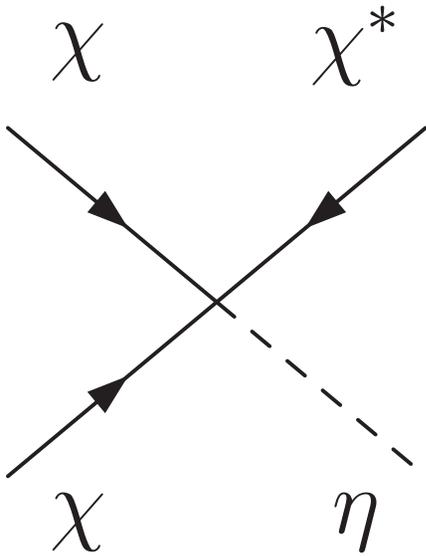
$$C_{\chi h \rightarrow \chi^*\chi^*} = -\frac{1}{2} C_{\chi\chi \rightarrow h\chi^*}$$

Case 1: η heavy, $\mu_1 \neq 0$: Semi-annihilation

$$\Omega_{DM} h^2 \simeq 0.1$$



Case 2: $m_\chi > m_\eta$, $\alpha_4 \neq 0$: Dark-conversion



Future directions

Phenomenology/Experiment:

- Mass/Spin determination; feasibility?
- Sub-GeV dark sector - scope for high intensity/fixed target experiments

Models:

- Many other nonabelian discrete symmetries
- Nonabelian discrete gauge symmetries
- Address hierarchy problem(s) (e.g. SUSY)

Summary

- What stabilizes dark matter?
- Discrete gauge symmetry:
 - Survey models based on $U(1)$ broken to Z_N
 - Direct detection of two DM species
 - New signatures of the Higgs
- Nonabelian Discrete Symmetry:
 - Minimal model based on group D_3
 - Cosmology: semi-annihilation and dark matter conversion